

Using Code Coverage Tools in the Linux Kernel

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Defining software reliability is hard enough, let alone ensuring it. However, most all software developers agree on the importance of testing. The often unspoken assumption with testing is that the test programs *cover* a majority of the source code written. A test covers a line of code if running the test executes the line. *Coverage* analysis measures how much of the target code is run during a test and is a useful mechanism for evaluating the effectiveness of a system test or benchmark.

The GNU development tool gcov allows developers to obtain coverage results for programs compiled with the GNU gcc compiler.

In this article, we learn how to instrument the Linux® kernel to generate code coverage data, and how to visualize results with tools from the Linux Test Project (LTP) [4].

1 Coverage Basics

Code coverage analysis is the process that allows us to determine the percentage of code within an application that was executed during the test process. The data gathered by using coverage analysis can be used to measure and improve the test process [6]. Coverage analysis can be performed in a variety of ways for producing different views of how a test process executes the code. A few types of coverage analysis are discussed here.

The first and most basic type of coverage analysis is usually called statement coverage analysis [1]. Statement coverage analysis breaks the code down into basic blocks. Basic blocks are the sections of code that exist between branches. Since these basic blocks do not cross branches, we can know that if any instruction in a basic block is executed, then every instruction within the basic block is executed the same number of times. Instrumenting basic blocks with counters provides a more efficient way of showing how many times each line of code in a program has been executed, without having to instrument every line.

Statement coverage analysis is what most people generally think of when they think of code coverage analysis, but it isn't flawless on its own. The following example shows one way it can fail:

```

int *iptr = NULL;
if(conditional)
    iptr = &i;
*iptr = j*10;

```

The example above will work fine when every line is executed (100% coverage). However, if the conditional is ever false, `iptr` will be null when dereferenced, exposing the bug. With statement coverage, one must know that 100% code coverage in a test process may not necessarily imply that the application is well tested.

Another type of coverage analysis is called branch coverage analysis [5]. Instead of generating data about how many times each line or basic block is executed, branch coverage looks at the branches between basic blocks. Branch coverage analyzes each branch to determine the possible paths through it and produces data to show which paths were taken and how often. As an added bonus, by knowing which branches were taken, statement coverage data can be derived. In the example above, branch coverage would have clearly shown that one possible branch (conditional failed) was never tested, exposing a hole in the test process.

A more sophisticated form of branch coverage also exists that handles complex conditionals. Many conditionals involve more than a single test that will pass or fail. Some conditionals involve complex logic that requires testing through all combinations. The better form of branch coverage analysis will correctly handle situations like the following example:

```

struct somestructure* p = NULL;

if(i == 0 || (j == 1 && p->j == 10))
    printf("got here\n");

```

If i is ever non-zero when j is 1, then the NULL pointer p will be dereferenced in the last part of the conditional. There are paths through this branch in both the positive and negative case that will never expose the potential segmentation fault if the conditional is only analyzed as a single pass or fail statement.

1.1 GCOV

Although there are many other types of coverage for dealing with a variety of corner cases, gcov only provides statement and branch coverage. In order to get coverage data, programs must be compiled by gcc with the `-fprofile-arcs` and `-ftest-coverage` flags. These options cause the compiler to insert additional instructions into the generated object code. This new code increments counters which identify sections of the code being executed. When the program is run these counters are incremented when the specific portions of the code are executed. When the program terminates the counters are dumped to a file. During the postmortem, the actual gcov program is used to process the counter file just created.

Unfortunately, until now gcov did not work on kernel code for two primary reasons. Although kernel files can be instrumented with gcc, the kernel never links with the system libraries that provide support

functions for gcov. Additionally, since the kernel never exits, counter data would never be generated. Getting coverage data from dynamic modules was another obstacle to kernel coverage.

In early 2002, the LTP team published a patch to the Linux kernel that addresses these issues and allowed developers to use the existing gcov tools to get coverage data from a running kernel [2]. A detailed description of the functionality provided by the patch can be found in our Ottawa Linux Symposium paper [3].

2 Using Coverage Tools

Once a program has terminated and the gcov counter data (*.da* files) exist, gcov is capable of analyzing the files and producing coverage output. To see the coverage data for a user space program, one may simply run *gcov program.c* where *program.c* is the source file. The *.da* file must also exist in the same directory.

The raw output from gcov is useful, but not very readable or organized for viewing source trees. The lcov toolkit produces a far more user friendly and organized output. lcov automates the process of extracting the coverage data using gcov and producing HTML results based on that data [4].

To produce coverage data with lcov, first download the gcov-kernel and lcov tools from the LTP website at ltp.sourceforge.net.

Apply the gcov-kernel patch to a test kernel.

```
patch -p1< gcov-<kernel version>.patch
```

General kernel configuration and compiling instruction is beyond the scope of this article. But, to enable gcov on the entire kernel, verify that the *GCOV kernel profiler* configuration option is selected. The gcov-kernel README file provides details on how to gcov enable portions of the kernel. After compiling and installing the gcov-kernel, download and install the lcov toolkit. The lcov toolkit provides options for manipulating gcov data.

lcov provides scripts to clear the gcov kernel counters.

```
lcov --zerocounters
```

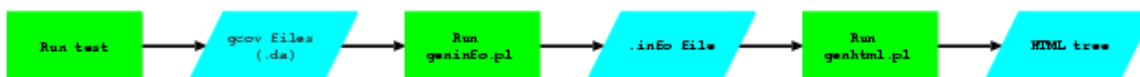


Figure 1: lcov Flowchart

The developer would run one or more tests to exercise the new kernel code. During the test, gcov-kernel counters are updated.

The basic process flow of the lcov tool is illustrated in Figure 1. Capture the gcov data by calling lcov with the capture option (-c), specifying an output file (-o).

```
lcov -c -o kerneltest.info
```

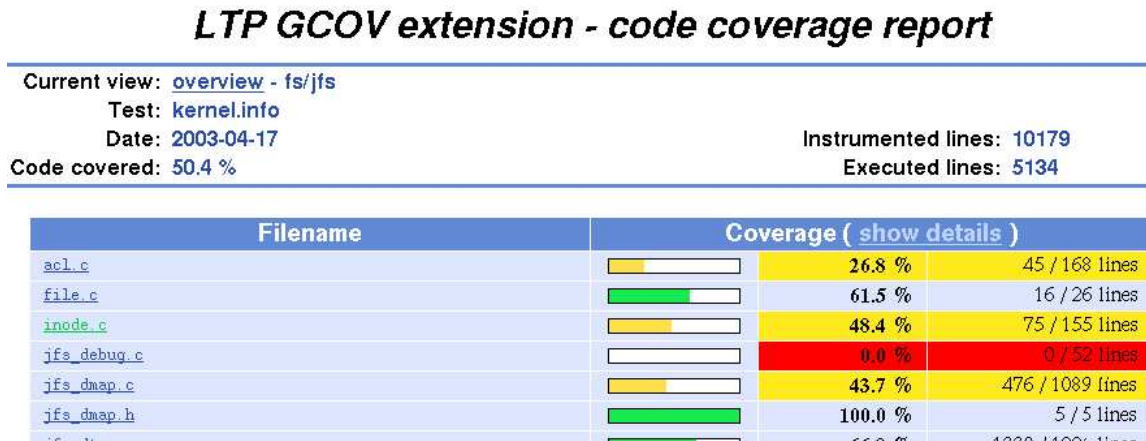


Figure 2: Partial lcov output for fs/jfs

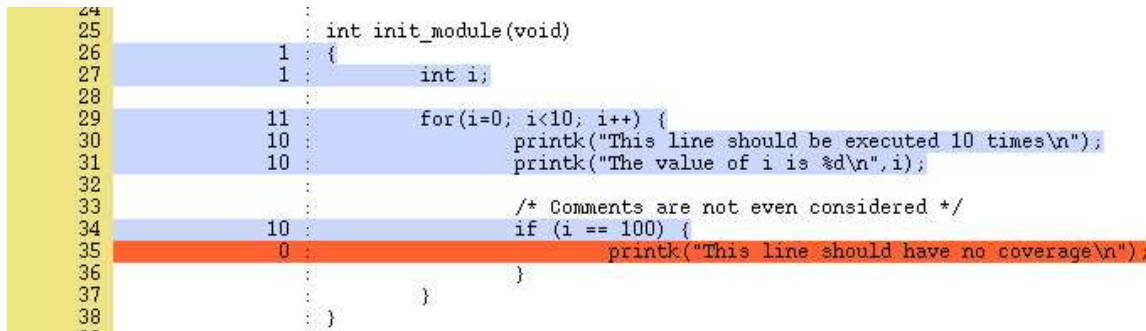


Figure 3: Example lcov output for a file

The lcov tool first calls gcov to generate the coverage data, then calls the LTP **geninfo** script to collect that data and produce a .info file to represent the coverage data. Once the .info file has been created, the **genhtml** script may be used to create HTML output for all of the coverage data collected. The **genhtml** script will generate both output at a directory level as illustrated in Figure 2 and output on a file level as illustrated in Figure 3.

```
genhtml -o [outputdir] kerneltest.info
```

The `lcov` tool can also be used for analyzing the coverage of user space applications, and producing HTML output based on the data collected. Using `lcov` with applications is similar to kernel usage. In order to analyze coverage, the application must be compiled with `gcc` using the `-fprofile-arcs` and `-ftest-coverage` flags. The application should be executed from the directory in which it was compiled, and for `gcov` to work on user space programs, the application must exit normally. The process for using `lcov` with an application is as follows:

1. Run the program following your test procedure, and exit.
2. `lcov --directory [dirname] -c -o application.info`
3. `genhtml -o [outputdir] application.info`

`lcov` can also be used to manipulate *.info* files. Information describing coverage data about files in a *.info* file may be extracted or removed. Running `lcov --extract file.info PATTERN` will show just the data in the *.info* file matching the given pattern. Running `lcov --remove file.info PATTERN` will show all data in the given *.info* file except for the records matching the pattern, thus removing that record. Data contained in *.info* files may also be combined by running `lcov -a file1.info -a file2.info -a file3.info... -o output.info`, which produces a single file (*output.info*) containing the data from all files passed to `lcov` with the `-a` option.

3 Results & Conclusions

The `gcov-kernel` patch overhead was estimated by comparing compile times for the Linux kernel. Specifically, each test kernel was booted and the time required to compile (execute `make bzImage`) the Linux 2.5.50 kernel was measured. Runtimes, as measured by `/bin/time`, show 91.62+1090.38 seconds of kernel+user time to compile the kernel without the `gcov-kernel` patch. A patched kernel took 113.17+1103.63 seconds to compile. Even though the patch increased the kernel time by about 23%, most applications spend a small percentage of their time in the kernel. In our test, the compile spent less than 10% of the time in the kernel, so the observed overall `gcov-kernel` patch overhead is about 3% of the combined kernel and user space runtime. See the Ottawa Linux Symposium paper [3] for more on the `gcov-kernel` patch overhead.

The real benefit of code coverage analysis is that it can be used to analyze and improve the coverage provided by a test suite. In this case, the test suite being improved is the Linux Test Project. 100% code coverage is necessary (but not sufficient) for complete functional testing. It is an important goal of the

LTP to improve coverage by identifying untested regions of kernel code. This section provides a measure of LTP coverage and how the gcov-kernel patch has improved the LTP suite.

The gcov-kernel patch and LTP tool and test suite make the valuable gcov software coverage package available to kernel developers. gcov allows developers to measure the effectiveness of their testing efforts.

References

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